THE ROLE OF IMPACT VELOCITY AND CHANGE OF VELOCITY IN SIDE IMPACTS

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ABSTRACT

The main injury mechanism in nearside impacts is normally linked to the relative impact velocity of a bullet vehicle or an object. The change of velocity of the target vehicle has been considered to have a minor role, at least for a nearside occupant. It has, however, been complicated to distinguish between impact velocity and change of velocity in real life accident analysis.

In the present study, the aim was to analyse real life side impacts to isolate the roles of impact velocity and change of velocity in relation to injury risk. The analysis method used was matched pairs used in a modified way, where different combinations of vehicles of varying mass ratios were studied according to relative injury risks to the driver. The data set used for the analysis was crashes in Victoria, Australia.

The results show, that while impact velocity is of major importance for the risk of injury, change of velocity also plays a major role in nearside impacts. In far side impacts, impact velocity is of minor importance compared to change of velocity. In reality, it must be stressed that they are highly correlated.

The result of the study, if validated further, has implications for crash test configurations and validation of side impact safety design. One outcome might be that cars of different masses should be tested at different speeds, or that movable barriers should be varied in mass and speed depending on the mass of the target vehicle.

BACKGROUND

Side impacts, or lateral impacts, has been subjected to research, development and regulation for several decades. The main mechanism for injury to the torso of the human body has been described as the forces acting on the body as a result of the intruding side structures (1,2). The velocity and the amount of intrusion has been linked to the relative velocity of the vehicle impacting the target vehicle (3,4). Nevertheless, the resulting change of velocity to the target vehicle has been used to consider the impact severity of the side impact (5,6,7). This has not been considered logical, as at least some of the injuries are likely to occur at a very early stage of the side impact, and not resulting from the change of velocity occurring later in the sequence. Depending on the mass ratio of the target and bullet vehicles, an identical relative velocity can result in a varying change of velocity, and vice versa. On the other hand, serious and fatal injuries in both near side and far side impacts are often located to the head and neck (6,8), where the change of velocity might appear logical as an approximation of the magnitude of the mechanical forces acting on the human.

The risk of an injury can be described as a dose-response function, where the dose is the amount and type of mechanical force acting on a human. A complex dose- response system such as a vehicle impact can be divided into several different sub dose-response systems according to the question under study. The actual dose to the human is sometimes substituted with the dose to the vehicle. In car impacts the dose is often referred to as the impact severity. Especially in frontal or rear-end impacts, this exposure dose is often given as the change of velocity that the vehicle undergoes in a crash. In side impacts, the dose is often given as the relative velocity of a vehicle impacting the target vehicle (9,10,11).

The understanding of the response is equally important, and that the adequate mechanical dose vary with the response studied. While the response could be related to the whole human body, it could as well be a certain injury or injury mechanism (11).

The knowledge on the dose response functions is fundamental in the understanding of how humans are injured, as well as a basis for prevention in terms of restraints, etc. The knowledge also serves as important input to crash tests and mathematical simulations as well as for setting injury criteria for human substitutes. Dose response functions are also important in understanding and developing safety evaluation or rating of new innovations or new vehicles (10,11).

There are different ways of calculating injury risk functions versus impact severity. The most common way is to relate measured or calculated parameters describing impact severity to injury risk. Traditionally, impact severity has been calculated by reconstruction of impacts. To date reconstructions of vehicle collisions are most often based on retrospective studies where static measurements of different parameters describing the circumstances in the collision are included. Vehicle deformations have usually been used as input for reconstruction programs, as for example Crash3, to calculate EBS or EES (12,13). If in a two-car collision the EES of both vehicles is known, the change of velocity for the involved vehicles can be calculated. Recently, crash recorders have been introduced and used as research tools (10,11,14.15)

Calculations of change of velocity with reconstruction programs have been shown to generate substantial measurement errors (16,17,18), which are very complicated to handle in analyses of risk functions. The numbers of errors have been found to be of an order that seriously influences the conclusions drawn from risk functions (Kullgren and Lie, 1998).

Studies have been presented showing injury risk versus measured change of velocity, by using on-board crash recorders (10,15), see Figure 1.

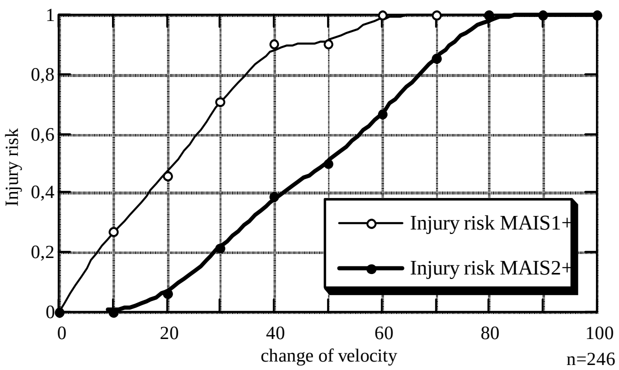

Figure 1. Injury risk versus change of velocity, MAIS1+ and MAIS2+.
(from Kullgren et. al., 1999)

An alternative way of calculating injury risk is by induced methods, for example by using paired comparison technique (19). Such methods would have the advantage of being used on large samples of readily available accident data.
In this study, the aim was to separate the role of impact velocity and change of velocity for nearside and far side occupants in side impacts.

In detail, the aim of the study was to:

- Present an alternative to the derivation of injury risk functions based on paired comparisons, and
- To apply the method on accident data material including side collisions in order to produce risk functions for a set of impacts and occupant seating.

METHOD

Basically, the distribution of change of velocity in car-to-car crashes can be calculated from the law of the conservation of momentum, where:

Delta v = $V_{rel} (M_2 / M_1 + M_2)$,

where V_{rel} is the relative velocity and M_1 and M_2 the masses of the two vehicles colliding.
This relation is true even if the two vehicles involved do not have a common velocity after the impact. If the masses are equal, both vehicles will undergo the same change of velocity. This method uses this fact, and that any deviation in mass can be transferred to differences in change of velocity, as long as the individual masses are known (Figure 2). Since the relative velocity, V_{rel} , is unknown the method cannot generate absolute figures, only risks relative to each other.

Instead of generating new risk functions, the method uses the change on the exposure distributions and the resulting change in risk.

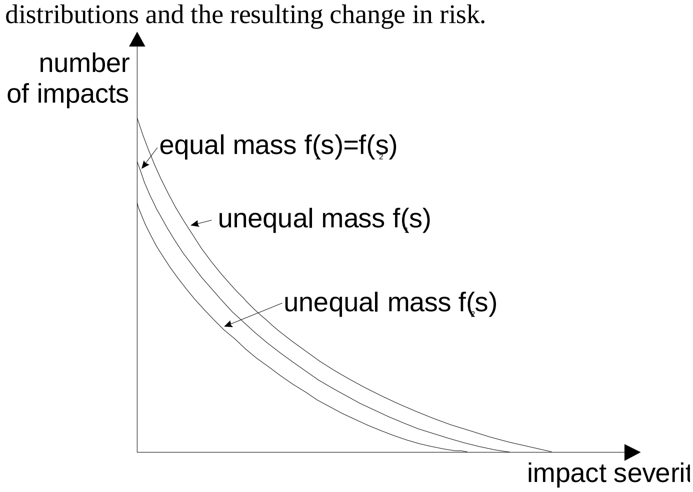

Figure 2. Impact severity (delta-V) for cars in matching crashes for equal mass: $f_1(s) = f_2(s)$ and unequal mass: $f_1(s) \neq f_2(s)$ where car 1 is of less mass than car 2

The basis for the statistical method is the paired comparison technique, where two car accidents are used to create relative risks. The method was initially developed by Evans (1986)(20), but has been developed further for car to car collisions by Hägg et. al. (1992)(21).

The assumption for the method is that the risk of injury is a continuous function of change of velocity. This assumption might conflict with safety features such as airbags that might generate a step-function. This would have to be further investigated. Another assumption is that injuries in one car are independent from the injuries in the other car, given a certain accident severity.

For a given change of velocity the risk of an injury is p_1 and p_2 in the two cars, respectively. For that change of velocity, the outcome of the accident is therefore:

Table 1
Probabilities of injury to driver in car 1 and 2 in a segment of impact severity

		Driver of Car 2		
		driver injured	driver not injured	Total
Driver of Car 1	driver injured	$n_i P_{1i} P_{2i}$	$n_i P_{1i} (1\text{-}P_{2i})$	$n_i P_{1i} P_{2i} + n_i P_{1i} (1\text{-}P_{2i}) = n_i P_{1i}$
	driver not injured	$n_i (1\text{-}P_{1i}) P_{2i}$	$n_i (1\text{-}P_{1i}) (1\text{-}P_{2i})$	
	Total	$n_i P_{1i} P_{2i} + n_i (1\text{-}P_{1i}) P_{2i} = n_i P_{2i}$		

Summing over all segments of change of velocities, the outcome will be:

Table 2

		Driver of Car 2		Total
		driver injured	driver not injured	
Driver of Car 1	driver injured	$\sum_{i=1}^{m} n_i P_{1i} P_{2i} = x_1$	$\sum_{i=1}^{m} n_i P_{1i} (1\text{-}P_{2i}) = x_2$	$\sum_{i=1}^{m} n_i P_{1i} P_{2i} + n_i P_{1i} (1\text{-}P_{2i}) = n P_1$
	driver not injured	$\sum_{i=1}^{m} n_i (1\text{-}P_{1i}) P_{2i} = x_3$	$\sum_{i=1}^{m} n_i (1\text{-}P_{1i}) (1\text{-}P_{2i}) = x_4$	
	Total	$\sum_{i=1}^{m} n_i P_{1i} P_{2i} + n_i (1\text{-}P_{1i}) P_{2i} = n P_2$		

The relative risk of an injury, for vehicle 1 to 2, given a certain change of velocity distribution is therefore:

$$R = (x_1 + x_2) / (x_1 + x_3) = \frac{\sum n_i P_{1i}}{\sum n_i P_{2i}} = \frac{\sum n_i P_{1i} P_{2i} + \sum n_i P_{1i} (1 - P_{2i})}{\sum n_i P_{1i} P_{2i} + \sum n_i (1 - P_{1i}) P_{2i}}$$

The method is unbiased for any combination where the vehicles are of the same weight; i.e. the mass ratio is 1. If the vehicles are of different weights, the two vehicles will undergo different changes of velocity, which will have to be compensated for. Generally, we can introduce any component, K, that will affect the risk of injury in either, or both of the vehicles. If we let K_1 denote this factor in vehicle 1, and K_2 in vehicle 2, this will lead to:

(1) $n_i P_{1i} P_{2i} K_1 K_2 / n_i P_{2i} K_2 + \ldots + n_i P_{1i} P_{2i} K_1 K_2 / n_i P_{2i} K_2 = \sum_{i=1}^{m} n_i P_{1i} P_{2i} K_1 / \sum_{i=1}^{m} n_i P_{2i}$

$= K_1 \sum_{i=1}^{m} n_i P_{1i} P_{2i} / \sum_{i=1}^{m} n_i P_{2i}$

To solve the equation, cars of different weights will be used, where the weights are known. K will therefore denote the role of change of velocity, and could be a constant, or a function of, say, change of velocity.

(1) is estimated by $K_1 (X_1 / (X_1 + X_3))$ (2) and, $K_1 = \frac{(X_1/(X_1+X_3))_{m_b}}{(X_1/(X_1+X_3))_{m_a}}$ (3) where,

m_a and m_b are mass relations in the matched pairs. These mass relations are transformed to relative change of velocity by

$$\frac{m_b}{m_a} = \left(\frac{m_2}{(m_1 + m_2)} \right)_b / \left(\frac{m_2}{(m_1 + m_2)} \right)_a$$

The analytical functions chosen to describe the risk functions have been applied simply using either a linear function or a power function. This issue would have to be further investigated using more advanced material.

It is obvious, that while the importance of a marginal change of velocity will be calculated, as well as parts of the risk function, absolute values cannot be given. If this is to be done, a key value must be brought into the equation.

In order to isolate the role of impact velocity, the data set was split in two in order to differentiate between two speed clusters. Just dividing the data set in speed zones below and over 60 kmh found the lower and higher speed clusters. The speed in itself had no role in the analyses, as the risk functions could be calculated for both individually. The injury risk for vehicles of identical mass ratios was found to be higher in the high-speed cluster, and by finding the injury risk where the risk of injury was identical for the bullet vehicles; it was possible to estimate the role of impact severity, at one point. Also by finding cases . The relative velocity, V_{rel}, was calculated, when the change of velocity was the same for the side impacted vehicle in the two sets of impacts, and the difference of V_{rel} was then the difference in the change of velocity of the bullet vehicle. Identical calculations were made for both near side and far side drivers.

MATERIAL

The material used was two car crashes, front-to-front and front to side, from Victoria Australia (1991-97). Only injuries leading to hospital admission were used. The source of the data is a combined set of both police and insurance data (TAC)

Although data of this kind is known to have some problems with quality, they are not likely to cause major biases of the results. While using only a few variables from the police records, the main quality issue lies with the under-reporting, and the lack of in-depth medical data. Under reporting of crashes would not lead to bias in the risk functions, but under reporting of injuries in a crash used in the analysis would bias the outcome. To which extent that is an issue in the current analysis is not known and would have to be further investigated.

RESULTS

Figure 3 shows the relative risk for drivers in side impacts for the driver in the frontal impact versus the driver in the side-impacted vehicle, for both near side and far side occupants. It can be seen, that while the risk of a serious injury is relatively higher for the driver in the side-impacted vehicle, it is lower for the far side driver than for the near side driver.

In more detail. It can be found, that the risk of a serious injury in a frontal impact increase approximately five times within the range 75% to 125% of the average change of velocity. On a more narrow segment, a 10% increase of the change of velocity, the serious injury risk increase approximately 30%.

In the side impacts with a far side occupant, the risk increase even more with a higher change of velocity. A 10% marginal increase of the change of velocity, increase the risk of a serious injury by approximately 40%. In relation to frontal impacts, the risk of a serious injury for a given change of velocity, is approximately 40% higher.

For occupants on the near side, the risk of a serious injury is even higher than on the far side. In general, it seems to be doubled compared to the far side occupant, for a given change of velocity. The marginal increase for higher changes of velocity, is almost 50% for a 10% increase of the change of velocity. It shows, that the most sensitive situation for an increase of the change of velocity among the three situations analysed, is the near side occupant in a side impact.

A further result of the study was also, that in average, the change of velocity was 15% higher when the car was hit on the passenger side, than on the drivers side. This result has clearly to do with traffic situations and traffic engineering, rather than being vehicle related.

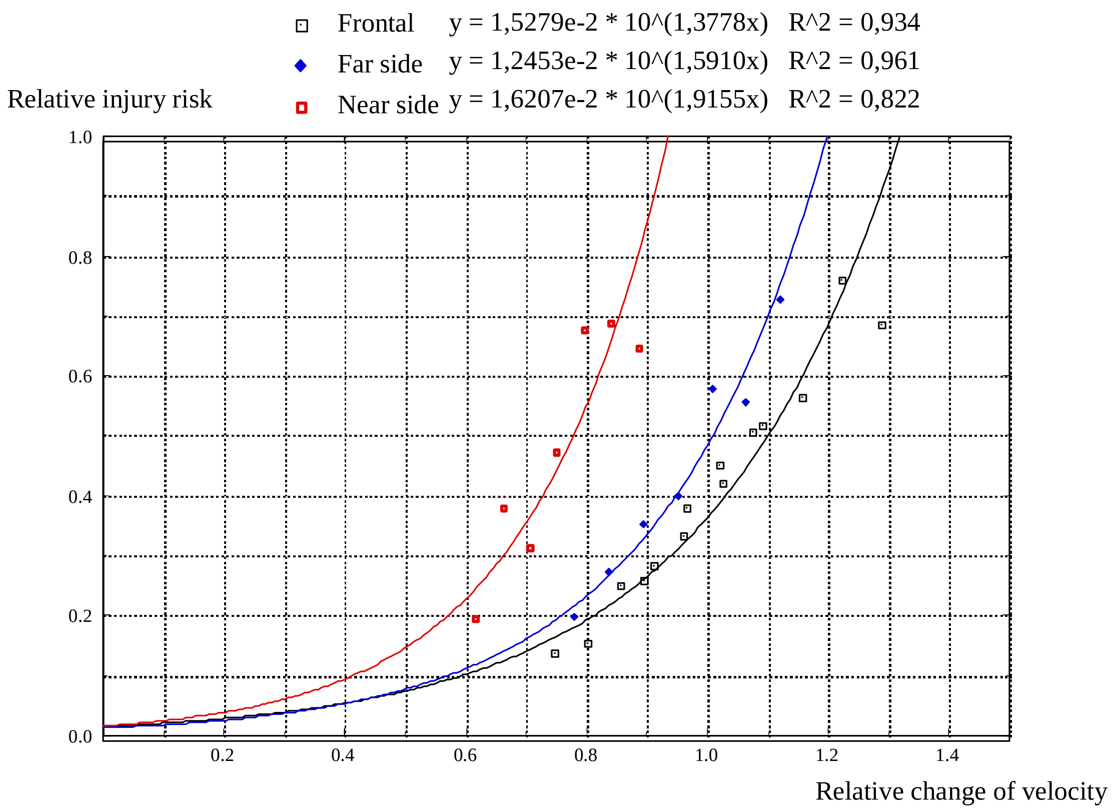

Figure 3. The relative risk of injury related to the relative change of velocity, for frontal impacts, far side occupants in side impacts, and near side occupants in side impacts.

In figures 4 and 5, the relative risk of injury in far side and near side impacts are shown in detail, where the data set was split into impact in low and high speed environments. In figure 4, far side impacts, in can be seen that the risk of injury is similar for the two situations where impact velocity is different. It could be calculated from the injury risk in the impacting car, that the impact velocity is 11% higher in the higher speed environment, but that this does not imply any higher injury risk in the impacted car for the same change of velocity. The conclusion is therefore, that the change of velocity is of importance, but not the variation of impact velocity given a certain change of velocity.

The above results are in contradiction to the results presented in figure 5. Here it can be seen, that the impact velocity plays a role, in that the two linear functions are different.. The line with the lower slope, represents crashes in the high speed environment, and the line with the higher slope the low speed environment. In order to get the same change of velocity of the impacted car in the low and high speed environment, the impact velocity in the low speed environment must be higher. This velocity is 11 % higher, and results in a 20% higher injury risk for the near side occupant, with an equal change of velocity. Still, change of velocity plays a major role in explaining the risk of injury also to near side occupants.

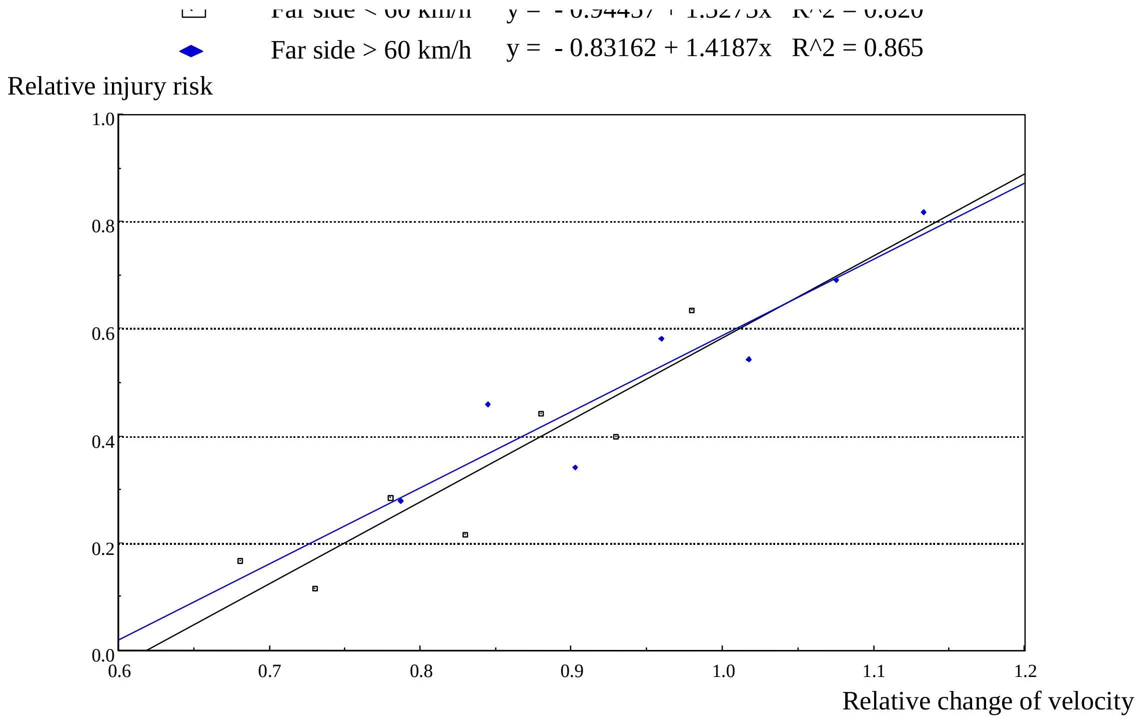

Figure 4. The relative risk of injury for far side occupants in side impacts, in speed limit areas below and over 60 km/h.

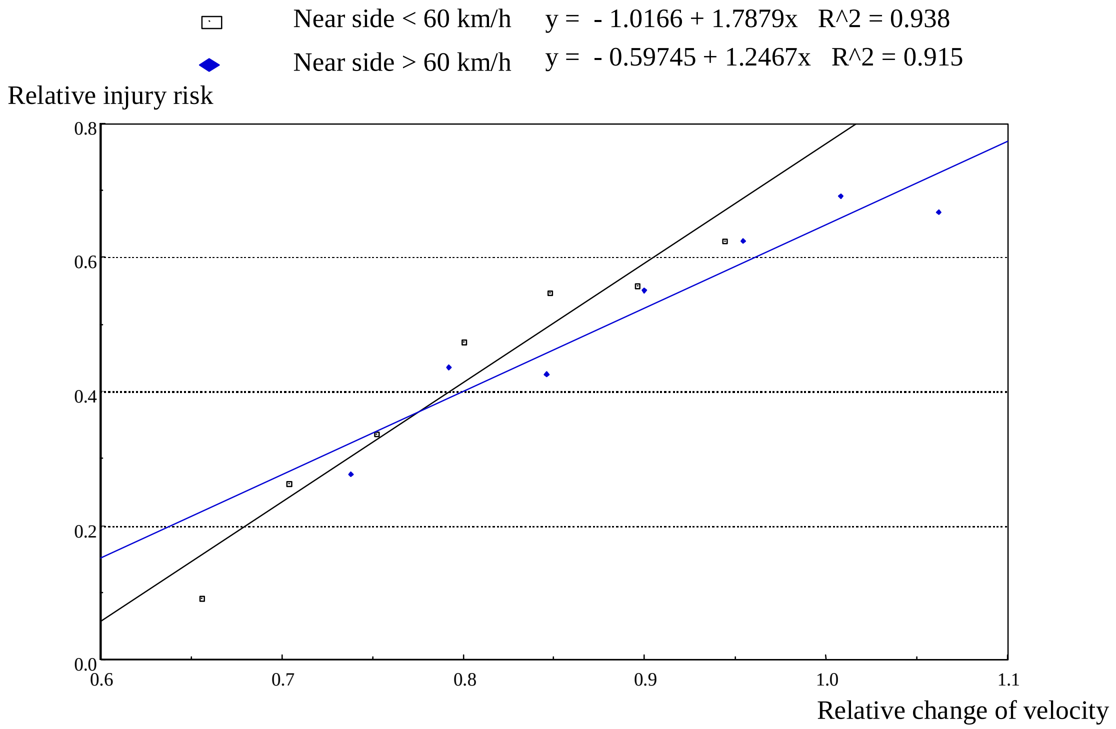

Figure 5. The relative risk of injury for near side occupants in side impacts, in speed limit areas below and over 60 km/h.

DISCUSSION

The method and the results presented in this study should be seen as an example of what can be achieved with the matched paired technique in combination with simple Newtonian physics. In this example it must be stressed, however, that there are a number of assumptions that must be fulfilled. Nevertheless, the results have to be explained in both engineering as well as statistical terms. In other words, if the statistical assumptions are valid, the mechanical implications are of great importance.

This study shows that it is possible to generate risk functions without accident reconstruction, although absolute functions in terms of figures on change of velocity cannot be given. This gives us a method to validate, and to modify, risk functions derived by other methods. These methods, if they are based on reconstruction, are subject to errors in a magnitude that can seriously affect the calculated relationship between accident severity and risk of injury. Kullgren and Lie (1998)(9) have shown that random errors in the impact severity term in the order of 15% or greater can affect the risk functions to a large degree. Errors in field data are often larger. Serious consequences can be foreseen by such errors in the field of crash protection. It is important to understand that while it is quite common to generate accumulated proportions of injuries related to change of velocity, the current method tries to actually generate true risk functions, which is the risk of injury for a certain mechanical dose (change of velocity).

The proposed method can also be used to validate injury criteria and results from mathematical and mechanical simulations. If such experiments are compared with the risk functions derived by the present method, increases in risks should fit to real-world data. If, for example, the risk of neck injuries in rear end impact is compared to dummy readings from impact tests, there should ultimately be a good correlation with the risk functions derived.

The method proposed can also be used to validate risk functions derived with methods based on reconstruction. While reconstruction normally would have to be based on limited accident data, mass data can be used to derive risk functions with the present method. It should therefore be possible to look at more or less any injury, even if it is rare. The method can also be used for studying the consequences of vehicle fleet down weighting on numbers of fatalities and injuries.

The limitations of the method presented herein are that only change of velocity and impact velocity can be related to injury. It is well known that change of velocity and impact velocity are not the only parameters influencing the outcome. This method will therefore never be the single method for deriving risk functions between dose and response for car occupants. On the other hand, it will take a long time to collect cases with more advanced methods, such as crash recorders. Another limitation is that the method currently can only handle continuous risk functions, and not step functions.

However, crash pulse recorders make it possible to relate crash pulse characteristics, as for example mean and peak acceleration, to injury risk, which is not possible if impact severity is calculated with traditional accident reconstruction techniques. Figure 8 shows an example of injury risk versus mean acceleration based on recorded crash pulses in real-world impacts (from Kullgren et. al., 1999).

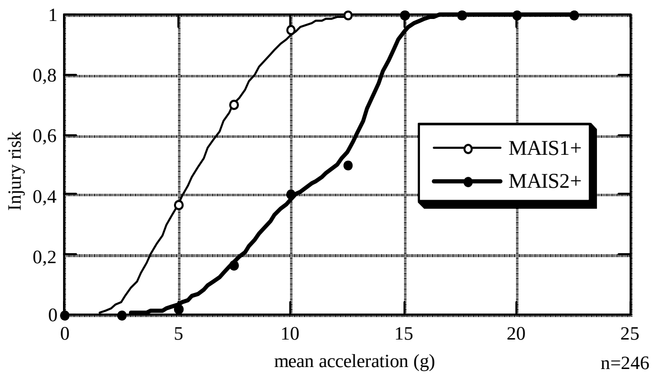

Figure 8. Injury risk versus mean acceleration MAIS1+ and MAIS2+
(from Kullgren et. al., 1999)

The method presented in this papaer is probably sensitive to errors, or approximations of vehicle weight. In this study, the service weight of the car was used, while this is not necessarily the weight of the car at the time of impact. Loading of passengers and cargo will have a certain impact on the figures, as well as modifications to cars.

The data set used is not the most perfect. The injuries should have been classified more in detail in order to have homogeneous groups of injuries and injury mechanisms. This is the reason for why the analysis of the risk functions were not focussed.

A development of the present method would be to further study the possibility to bring several types of injuries together in order to correctly position their respective risk functions in relation to each other. This will open interesting possibilities for comparing different kinds of injuries, and could be related to more complex mathematical and mechanical simulations.

The results in themselves offer some interesting findings, in that it can be shown, that side impact injury risks are partly related to impact velocity, but also change of velocity. This is not in absolute contradiction to earlier results (4,5,6,7), but it serves as an input for modifying test methods and validation of safety technology. It is normally considered relevant to express impact severity in a side impact with the impact velocity, as it is known, that some injuries occur as a result of the velocity of the intruding door. The results of this study shows, that this is not enough as an explanation to injuries to near side occupants. The implication of the results might be, that in order to keep impact severity constant for vehicles of different size, the mass of the moving barrier should vary in relation to the mass of the impacted vehicle. In that case, both impact velocity and change of velocity could be held constant. The methods used today, with constant impact velocity and mass of the barrier, should generate a very simple test for a high weight vehicle compared to a low weight vehicle, if all serious injuries are taken into consideration. A 50% higher mass in a side impact would according to the findings in this paper, result in a 100% higher risk of a serious injury.

In far side impacts, change of velocity seem to be the main explanatory factor to risk of a serious injury, while variation of impact velocity for a given change of velocity does not seem to add or reduce the risk of injury. The risk function in itself for far side occupant injury risk, is similar to the injury risk in a frontal impact. It is also obvious, that the impact severity used to optimise occupant protection, should be done in velocities close to the frontal impact, and definitely higher than for near side impacts. At the same time, it seems important to vary the test conditions to mirror that the change of velocity is the main injury producing parameter. It might be advised also here, that if moving barriers are used, the mass of the barrier should match the mass of the impacted vehicle.

An another consequence of the findings, that risk of injury is not only related to the relative velocity of the impact, but also the change of velocity, is that car safety rating systems based on matched pairs (21), are also valid when using mass relations to control for impact severity. If only impact velocity would have been of importance for side impacts, there could have been a case for that side impacts should be controlled for in a different way, simply by not controlling for the change of velocity. Following results of this study, it seems valid to continue to control for the impact severity in the same way for both frontal and side impacts.

CONCLUSIONS

- The matched pair technique can be used for generating injury risk functions simultaneously for several crash modes.
- Far side lateral impacts generate a higher risk of serious injury than frontal impacts at the same change of velocity.
- Near side lateral impacts generate a higher risk of serious injury than far side lateral impacts for the same change of velocity.
- Both change of velocity and impact velocity play an important role as input impact mechanical dose linked to injury risk in near side lateral impacts.
- Only change of velocity is adequate as input impact mechanical dose linked to injury risk in far side lateral impacts.

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